# Limits on the Hubble Constant from the dis ance of M100

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Abstract

Because of its location in the Virgo cluster our recent measurement of the distance of Ml 00 has an impact on the calibration of all of the extragalactic secondary distance indicators which reach beyond Virgo and define the expansion rate. We examine the consequences of a 17 Mpc M 100 distance, questioning its consistency with supernova and other distances.

The distance of h4100 provides two separate constraints 011 the Hubble Constant. First, it verifies the emissivity calculations for type 11 supernovae. These models, fitted to SN1987A, have recently been used to measure host galaxy distances beyond 104 kin/s recession velocity. Second, it constrains the distance of the Virgo c.luster, which in spite of its apparent complex structure, provides an effective calibration for a set of reliable and well-usd secondary distance indicators.

Reviewing the type 11 supernova distances for three galaxies with Cepheid distances, we find consistency, which supports the recent SN result $H_0$ = 73 ± 11 km/sec/Mpc. This support is independent of where M100 lies in the Virgo c.luster. Reviewing the Hubble recession velocity (cosmological redshift) of the Virgo c.luster the, we find $H_0$ = S1 ± 11 km/sec/Mpc, plus an additional uncertainty arising from the extended nature of the Virgo cluster.

Employing the Virgo cluster as calibrator, we obtain measurements of the Hubble Constant from extant surface brightness fluctuation measurements, elliptical galaxy velocity dispersion measurements, the Tully Fisher relation, and the type Ia supernova standard candle. These yield $H_0$ = 84 ± 16, 76 ± 10, 82 ± 11, and 71 ± 10 km/sec/Mpc respectively. All of these are consistent, but they are all subject to the additional uncertainty from Virgo's line-of-sight depth.

We explore a number of simple models of the strut.turc of the Virgo cluster; these support the recent conclusion of Freedman and coworkers that the appropriate uncertainty to attach to the Hubble Constant from the Cepheid distance to Virgo is 20%. A value of $H_0$ = 80 ± 1'[ km/sec/Mpc is consistent with all the data discussed herein. Confidence limits with 95% significance can be assigned to the interval 50 < $11_0$ < 1 ()() kill /scc./h4]~c..

Further work in this program should be expected to identify the systematic differences between the distance indicators investigated here and constrain the Hubble Constant to 10% accuracy.


Key words: Cosmology: distance scale

## 1. Introduction

Measurement of the distance of N4100 from Cepheid variables (Freedman et al 1994) is a major milestone in the quest for an accurate Value of $H_0$. The Hubble Space Telescope key project to determine the extragalactic distance scale aims to measure $H_0$ to 10%. To achieve this goal will require Cepheid distance measurements for some 20 galaxies within a redshift of approximately $10^3$ km/s. These galaxies in turn will calibrate five secondary distance indicators which will extend the volume over which the expansion rate has been measured to some $JO^6$ $Mpc^3$.

The purpose of this paper is to assess the impact of the distance of M100 on the extragalactic distance scale. In its way the Virgo cluster is as significant a junction in the distance scale as the Magellanic Clouds, permitting a consistency check on many secondary distance indicators. We are particularly interested in whether supernova distances are consistent with global indicators of galaxy distances based on their stellar populations. We examine whether 11 S'1' Cepheid distances are tending to converge or maintain a bimodal extragalactic distance scale. We begin the process of seeking out systematic differences between secondary distance indicators. Our objective is not to present an *ab initio* recalibration of the distance scale but rather to use the M100 distance to constrain the global value of $H_0$, and assess the remaing degree of uncertainty in its value.

We find that the measurement of M100's distance progresses the calibration of a number of these secondary distance indicators. Freedman et al (1994) considered the redshift of Virgo and the distance of Coma in order to estimate $H_0$. The additional secondary distance indicators considered here support the conclusions of that work. The net result is a very significant constraint on the Hubble Constant.

## 2. The Mean Distance of the Virgo Cluster

M1 00 is a *bona fide* member of the Virgo cluster, well within the cluster confines in velocity space, as shown in Figure 1. The concentration on the sky of galaxies in this cluster is clearly delineated in Figures 1 and 2. M 100 lies within the classical 6° circle of de Vaucouleurs (1 961), and just outside the last x-ray contour in the ROSAT map of Bohringer (1 994).

Marked substructure exists in the Virgo cluster (Huchra 1985, Bingelli, Sandage & Tammann 1 985) with member galaxies exhibiting a spread in surface brightness fluctuation distances from 11 to 19 Mpc (Tonry et al 1990). We must therefore consider whether M 100 is associated with the central concentration or the fringes of the c.luster. Our goal is to place confidence limits on the distance of the Virgo cluster.

There are four relevant and quan titative constraints.

1. We have the result of Freedman et al (1994) that the distance of M100 is 1 7.1±1.8 Mpc.

2. The Tully Fisher (TF) relation for the Virgo cluster is a second constraint. Pierce and Tully (19S8) find that M100 is 2.8 ±2.3 Mpc more distant than the mean in their optical and in frared photometric study of the Virgo TF relation. However, the inclination of the disk of M100 to the line of sig ht is only 27 ±3 degrees, as estimated kinematically (Warmels 19SS), and this low value detracts from the significance of M 100's residual in the TF relation.

3. Fouque et al (1 992) provide the most comprehensive study of the TF relation in Virgo. The galaxies within 2 degrees of M100 have a mean residual 0.13 ± 0.?4 mag brighter than the TF relation for galaxies within 2 degrees of M87.

4. We note that Pierce et al (1 994) have recently measured the distance of the galaxy NGC 4571 from three Cepheid variables identified with CFHT. They find 14.9 ± 1.2 Mpc.

More subjective criteria offer little insight into the location of these galaxies relative to the cluster mean. Sandage and Bedke (1 985) classify the resolvability of NGC 4571 as "excellent", but M 100 as '[fair'). These are the two extrema of their scale.

These constraints are consistent with the notion that M 100 is a member of the Virgo cluster, whose centroid is at 17 Mpc. We examine the uncertainty in that distance with some parameterized models of the cluster in §9.

## 3. The Cosmological Redshift of the Virgo Cluster

The mean redshift of the cluster corrected to the centroid of the 1 meal Group is 10'(3 ±50 km/s (Huchra 198 S). Bingelli, Sandage & Tammann (1987) have argued for a mean heliocentric velocity some 57 kin/s lower than Huchra's 1151 ± 3S kin/s. They consider a number of Huchra's galaxies to be background, but the difference is hardly significant. On the other hand, the velocity of M87 is 140 kin/s higher at 1292 km/s. Another point of contention is the velocity of the centroid of the Local Group, a further 40 km/s difference between the two groups and ill the same sense. We consider Huchra's value of the mean redshift to be the best estimate, but adopt a 'i'% uncertainty as a standard error.

A model fit to the TF relation for 30S spiral galaxies in the Local Supercluster by Aaronson et al (1982) yielded 331 ± 41 km/s for the infall of the Local Group into the mass concentration centered on Virgo. The model is analogous to that for Galactic rotation in that there is a local standard of rest, which is a pattern velocity constant on shells of constant radius from the Virgo cluster (250 km/s locally), and a local random velocity (S0 km/s in the Virgo direction). Subsequent work by Tonry et al (1 992) with more accurate distances from surface brightness flue.t,udtiolis confirm that result, yielding 340 ± 80 km/s (90% confidence limits). Jerjen& Tammann (1993) obtained 240 ± 40 km/sec for the infall velocity from an analysis of more distant Clusters (see also Sandage & Tammann 1 990). Han and Mould (1990) argue that a still lower estimate by Faber and Burstein (19SS) (85 133 km/s) is an artifact of their analysis. Averaging the first three estimates and combining this with the mean observed velocity of 1 073 ± 70 kln/see, we find that at the distance of Virgo, the expansion rate is 1380 ± 90 kin/s. This is consistent with Han & Mould's more detailed model for the TF data; they obtained 1422 ± 43 km/s. The Hubble constant we derive from the cosmological redshift of Virgo is $H_0 = 81 \pm 11$ km/s/Mpc. The uncertainty is derived from the distance and velocity uncertainties taken in quadrature. There is an additional uncertainty arising from the extended nature of the Virgo cluster.

## 4. Supernova 1979C

The distance of M100 has been inferred from the photospheric expansion of SN1979C measured photometrically and kinematically by Schmidt et al (1994). Their result, $15 \pm 4$ Mpc, is fully consistent with the Cepheid distance for M100, but is limited mainly by the large and uncertain apparent extinction of the supernova.

There are now four galaxies with Cepheid distances whose type II SNe yield EPM distances. They are the LMC ($49 \pm 3$ kpc from SN1987A), M81 (no final result because of the peculiarity of SN1993J[1]), M101 ($7.4^{+1}_{-1.5}$ Mpc from SN1970G), and M100 ($15 \pm 4$ Mpc). Wheeler et al. (1993) find a distance of $4.2 \pm 0.6$ Mpc for M81, which is consistent with the Cepheid distance (Freedman et al 1994b). Other primary distances are $51 \pm 3$ kpc for the LMC (Feast 1991, 1994), and 7.5 Mpc for M101 (Kelson et al 1995).

[1] See Schmidt et al (1993).

The distance ratio PL/EPM is $1.02 \pm 0.08$ for the LMC, $0.97^{+0.23}_{-0.17}$ for M101 and $1.13 \pm 0.28$ for M 100. These constraints, taken together without any weighting, amount to 90% confidence that empirical recalibration of EPM distances will be limited to multiplicative factors in the: interval (0.86, 1.24). The relation of the data to this interval is shown in Figure 4. Two more points can be anticipated in Figure 4 from discovery of Cepheids in galaxies under study with HST in Cycle 4.

Thus there is no evidence that, any empirical recalibration of EPM is required at present by the Cepheid data. EPM provides independent and consistent constraints on the Hubble constant, currently yielding $H_0$ = 734 11 km/s/Mpc (Schmidt et al 1994).

## 5. supernova Ia Standard Candles

The Hubble diagram for type Ia SNe at maximum light is discussed by Sandage and Tammann (1 993). The mean value of V(max) for 6 well observed SNeIa in the Virgo cluster is 12.13 ± 0.14 msg. Scaling the prototypical SN1937C from 4.8 ± 0.3 Mpc in IC 4182 to our Virgo distance of 17 ± 2 Mpc, implies a visual magnitude of 12.01 ± 0.25 mag (Jacoby and Pierce 1994). The same calculation for SN1972E in N5253 (Sandage et al 1994) yields 11 .69 ± 0.25 mag, which would therefore appear to have been an unusually luminous event. Hamuy et al (1995) assert that its high luminosity is due to its slow decline rate (Phillips 1993).

Like the type 11 SNe, the type Ia SNe offer a way to extend our knowledge of the expansion rate from the Local Supercluster, where the high density decelerates the expansion, to the freely expanding region outside it. The new estimate of type Ia absolute magnitudes based on the six Virgo supernovae permits a determination of $H_0$ from the 21 galaxies[2] at redshift exceeding 3000 km/s collated by Sandage and Tammann (1993) and Tammann & Sandage (1994) . This yields $H_0$ = 71 ± 7 km/s/Mpc plus an extra uncertainty arising from the extended nature of the Virgo cluster. Addit ion to this Virgo supernova calibration of SN1937C and SN1972E, would yield $H_0$ = 69. The Magellanic type galaxy 1(;41S2 and the amorphous galaxy NGC 5253 are not necessarily appropriate calibrators, however.

[2]The supernovae selected by this cut in redshift are 1959C, 1961D, 1962A, 1962E, 19661{, 1969C, 196 8E, 1970J, 19'/211, 1972J, 19'(3N, 1974.1, 1975O, 1976J, 1990af, 1991ag, 1992P, 1992ac, 1992aq, 1 992bc, 1 992bo.

Our results are consistent with the discussion of type Ias by Reiss, Press & Kirshner

(1994), who find $H_0 = 67 \pm 7$ km/s/Mpc, but inconsistent with the conclusion of Sandage et al (1994) who find $H_0 = 55 \pm 8$ km/s/Mpc by calibrating V(max) with Cepheid distances for IC4182 and N5253. The gap could be bridged if the mean Virgo supernovae were 19 Mpc distant (which is not ruled out by the Virgo models considered in the Appendix) and if Hamuy et al are correct that the effect of neglecting the peak luminosity decline rate relation is to underestimate $H_0$ by 15%

Further work will sharpen SNeIa as tools for distance measurement, including more attention to the correlation of V(max) with decline rate and dependence of V(max) on galaxy type (Van den Bergh and Pazder 1992). A future calibration will benefit from additional Cepheid distances of both field galaxies and clusters such as the Fornax cluster.

## 6. The Tully Fisher relation for clusters

Mould et al (1991, 1993) present I-band TF relations in an all-sky sample of 22 clusters of galaxies reaching 7500 km/s, and Aaronson et al (19S5) provide a pioneering study of 10 Arecibo clusters in the H-band within the distance of the Hercules cluster. The Virgo cluster materially adds to the existing field galaxy calibration of the TF relation (Freedman 1990). With the addition of the M 101 group galaxies to the Freedman calibrators, the total number of galaxies contributing to the combined H-band calibration summarized in Table 1 is 24. The equation of the regression line shown in Figure 5 is:

$$H^{abs}_{-0.5} = -21.32 - 9.53(log\Delta V(0)_{20} - 2.5)$$

where $\Delta V(0)_{20}$ is the 21 cm profile width and $H^{abs}_{-0.5}$ is a measure of the infrared flux. The quantities are defined in the original references. The intercept in this regression is 0.09 and $0.28 \pm 0.12$ mag brighter than those obtained respectively by Aaronson et al (1980) and Freedman (1990). The HST Key Project will effectively double the number of calibrators in Figure 5 when completed. With the new Virgo distance the calibration relation for I-band Tully-Fisher becomes:

$$I^{abs} , \cdot 20.70- 9.77(log\Delta V(0)_{20} - 2.5)$$

The value of the Hubble Constant that follows from applying these calibrations to clusters beyond 4000 km/s, neglecting the effect of perturbations to the 11 ubble flow and the Virgo depth uncertainty, is $11_0 = 86 \pm 11$ km/s. If we exclude clusters within 45° of the Great Attractor (Lynden-Bell et al. 1988) (and its antipode), noting the evidence for large scale flows (Mathewson et al 1993, 1994), we obtain $11_0 = 82 \pm 11$ km/s/Mpc. Again, there is an additional uncertainty arising from the extended nature of the Virgo cluster.

Other factors which limit the accuracy of this calibration are the depth of the Virgo duster, which introduces au artificial scatter into the relation in Figure 5, and the possibility that the Tully - Fisher relation is different in clusters and the field (Bernstein 1994, *c.f.* Han, Mould & Bothun 19S9). Further observations of field Tully-Fisher calibrators with HST will address these issues.

## 7. Other Secondary Distance Indicators

### Surface Brightness Fluctuations

Tonry et al (1 990) and Ciardullo, Jacoby & Tonry (1 993) have measured surface brightness fluctuat ions (S111") in 11 Virgo galaxies. Employing their current calibration, whose zeropoint is basal on early type galaxies in the Local Group,

$$M_I = - 1.50 + 4(V - I - 1.15)$$

where $M_I$ is the absolute magnitude of a galaxy's SBF in the I band and V I is the color of the galaxy, onc obtains a distance of $15.3 \pm 1.1$ Mpc. Adjusting the zeropoint to the 11% larger Virgo distance wc find from Cepheids, one can then examine the expansion rate of the most distant galaxies in the available sample. Tonry (1994, priv. comm.) has three galaxies with SBF measurements with $v_{CMB} > 4000$ km/s. These yield $H_0 = 84 \pm 16$ km/s.

, It is premature to modify the current calibration on the basis of a Virgo distance which is more uncertain than the distances of Local Group galaxies now employed by Tonry. But we note (i) that groups of early type galaxies with Cepheid distances will provide such a calibration] and (ii) that when we reach out to large distances with SBF, we obtain constraints on $H_0$ consistent with those from other secondary distance indicators.

### The Globular Cluster ant] Planetary Nebula luminosity Functions

Tammann (19s8) has Used measurements of the globular cluster luminosity function (GCLF) to derive a distance modulus of 31.7 mag for the Virgo cluster. Secker and Harris (1 993) argue that the data are compatible with a modulus of 30.9 mag. The M100-bascxl Virgo distance modulus by Freedman et a] of 3]. ] 5 :l 0.36 mag lies between these extremes. Study of a larger and more distant sample of galaxies to investigate the GCLF more fully will benefit from the high resolution of WFPC2. Since the method has not yet been applied beyond the Virgo cluster this method dots not offer us a significant constraint on the global value of $H_0$ at this stage.

A distance of the Virgo cluster of 17 :l 3 Mpc is consistent with that found by Jacoby et al (1992) from the Planetary Nebula Luminosity Function (PNLF), 15.4 :l 1.1 Mpc. Like the GCLF, the PNLF is currently limited in application to the Local Supercluster. With our current focus on applying secondary distance indicators at larger redshifts, we do not consider the PNLF further at present.

## 8. The Comoving Frame at the Coma cluster

TF data place Coma 3.69:1 0.16 mag behind Virgo according to Aaronson et al (19S.5) and ($D_n, \sigma$) data yield 3.74 :l 0.12 mag according to Faber et al (19S5). These empirical uncertainties are the dominant ones in extending Virgo's distance in Mpc to Coma. The significantly larger redshift of the spirals than the ellipticals in Coma is a 4% effect and of lesser importance. The redshift of Coma is $v_{hel}$ = 6942 :l 73 km/see (Zabludoff et al 1 993).

In the reference frame of the cosmic microwave background $v_{CMB}$ = 7197 ± 73 km/sec. Freedman et al (1994) employed this ratio to derive the Hubble Constant.

Mould et al (1993) fit a number of models to the velocity field within 7500 km/s and conclude that the expansion rate of the comoving frame is 7170 ± 125 km/s at the distance of Coma. With the new value of the Virgo distance (but without at this stage factoring in the extended cluster uncertainty) this yields $H_0$ = 76 ± 10 ii]])/s/h4])~. in agreement with Freedman et al.

In a provocative paper Turner et al (1992) have questioned whether the classical approach to the extragalactic distance scale is capable of measuring a global value of $H_0$ in the presence of a velocity field w'hit]] exhibits large scale flows. The results of their numerical experiments can be summed up in the following alarming illustration: "Even if the local expansion rate is known to be 80 ± 8 km/s/Mpc out to 30 $h^{-1}$ Mpc in the North Galactic Cap, the 95% confidence limits on the true global value of $H_0$ is 50 128 km/sec/Mpc in a CDM model."

With WFPC2 we do not expect to be able to measure distances directly with Cepheids very far beyond the Virgo cluster, where the expected *rms* difference between loud and global $H_0$ is 45% in current CDM. The subject of the present paper, however, is the calibration of secondary distance indicators whose effective range extends beyond the Coma c.luster. At Coma the same *rms* difference has fallen from 4 5% to 3% in CDM according to Turner et al.

Empirical evidence that real velocity fields present no larger problem than these calculations suggest is provided by:

(1) an all-sky survey of Tully-Fisher distances to clusters of galaxies

(2) an all-sky survey Of brightest cluster galaxies (Lauer & Postman 1994)

(3) the EPM data set.

These data are collected in Figure 6. Sources of TF cluster data are Aaronson et al (1986), Mould et al (1991, 1993), and Han & Mould (1992). The data have not been normalized to a common value of $H_0$, although Figure 6 is very similar, whichever of $H_0$ = 82 (§6), 73 (§4), or 80 km/sec/Mpc (Lauer & Postman) one adopts as a common value.

We can hypothesize a 'bubble model' in which $\delta H/H_0 \sim 0.5$, that is, $H_0$ = 75 km/s/Mpc within the distance of the Coma cluster and $H_0$ = 50 outside that radius. Figure 6 shows clearly that these data rule out a model with such a large difference between local and global $H_0$. Indeed, Lauer & Postman (1992) conclude that $\delta H/H_0 < 0.07$ within the volume shown in Figure 6.

Such a model is also heavily constrained by the isotropy of the cosmic microwave background on 1° scales. One hundred Mpc, which is approximately the radius of the volume enclosing Coma, corresponds to 1° (12′) on the surface of last scattering for $\Omega = 1(0.2)$. The requirement that $\delta H/H_0 \sim 0.5$ in a 'bubble model' of this type implies a three times larger density perturbation than is represented by the Great Attractor (Lynden-Bell et al 1988). Bertschinger et al (1990) show that a Great Attractor would evolve from $\Delta T/T = 1.7 \times 10^{-5}$ in an $\Omega = 1$ Universe. Schuster et al (1993) have measured $\Delta T/T < 1 \times 10^{-5}$ on 1.5° scales. A low density Universe would relax these constraints considerably (Fullana et al 1994).

## 9. Discussion

There are only two independent constraints on $H_0$ in the preceding sections. The first is contained in §4 (EPM) and the second in §§ 3,5, and 6, involving the additional assumption that we have successfully constrained the distance of the Virgo cluster. The discussion of EPM in § 4 appears to rule out $H_0 < 73/1.24 = 59$ km/sec/Mpc at the 90% confidence level. From a similar upper bound our verification of the EPM calibration yields $59 < H_0 < 89$ km/sec/Mpc with 90% confidence.

The constraint which M 100 puts on the distant.c of the Virgo cluster is a more complex issue. Associating M 100 with a cluster core of a certain structure, Freedman et al (1 994) obtain $H_0 = 80 \pm 17$ km/s/Mpc. Models of the cluster discussed in the Appendix consider the distances of MIOO and NGC 4571 as a constraint on the cluster distant.c. The models assert that the cluster distance is *probably* less than 19 Mpc; i.e. they yield a constraint which is no stronger than that adopted by Freedman et al. They rule out a mean cluster distance exceeding 22 Mpc at the 95% confidence level. The other tail of the distribution (d <11 Mpc) is similarly excluded. These considerations (and velocity uncerta inties are negligible by comparison) yield $55 < H_0 < 105$ km/sec/Mpc with 90% confidence.

Formally, under these two conditions $H_0$ lies in the interval (50,100) with more than 99% confidence, but it is not hard to find other scenarios to relax this constraint significantly. Suppose:

(1) The early type galaxies in Virgo are associated with component B (the smaller one) of the model

(2) The infall velocity of the Local Group is actually 2 $\sigma$ lower than estimated in §3, i.e. 220 km/sec (Tammann and Sandage 1 9S5)

Even these assumptions, however, require $H_0 > 53$ km/sec/Mpc. In Model 8 component B is closer than 24.5 Mpc with 95% confidence. This illustrates that wc have a strong lower imit on $H_0$.

It is not a completely unequivocable limit, however. To exemplify this, consider one urther possibility, whose likelihood it is hard to quantify, which might concei vably release the Hubble Constant from the present Virgo cluster constraints.

(3) The velocity of component B with respect to the centroid of the Local Group is that of M49, i.e. 847 km/sec.

This would allow $H_0$ = 44 km/sec/Mpc. We exclude this possibility, however, as the redshift of M49 dots not seem to be relevant to Virgo cluster calibrators of any of the secondary distance indicators we are using here.

We can see from the foregoing that we are dealing with a complex situation in Virgo (Jacoby et al 1992); constraints on $H_0$ will therefore inevitably remain looser than those which can be obtained from a simpler cluster such as Fornax.

The present discussion]] contrasts strongly with that of Pierce et al (19{14 ) who obtain $H_0$ 87 ± 7 km/s/Mpc. The error budget in the Hubble Constant determination tabulated by Freedman et al (1994) contains 12 terms of which the dominant ones are uncertainties in the distance of the LMC, the extinction of the Cepheids, and the extended nature of the Virgo cluster. Each of these uncertainties is as large as the uncertainty in $H_0$ quoted by Pierce et al. Pierce et al have given little consideration to these matters, concentrating, appropriately enough since they detected only 3 Cepheids in NGC 4571, on the width of the PL relation as the primary uncertainty in their result. We assert that, contrary to the optimistic view of Pierce et al, the confidence limits that can be put on $H_0$ at this time are those discussed herein.

## 10. Summary

In summary, the distance of M100 impacts the extragalactic distance scale in two ways, first in its own right as a calibrator of EPM, and second, by providing the distance of the Virgo cluster for the TF relation, the $(D_n, \sigma)$ relation, the SNIa standard candle, and surface brightness fluctuations. With the confirmation of the EPM calibration provided by SN1979C, EPM yields $H_0$ , 73 ± ]] km/s/Mpc . Assuming a Virgo cluster distance of 17 ± 3 Mpc, the other secondary distance indicators yield $H_0$ = SO ± 16 km/sec/Mpc. The uncertainty in the first case is dominated by the observational data pertaining to SN1979C . in the second case the uncertainty is dominated by the depth of the Virgo cluster.

In combination these results strengthen the conclusion of Freedman et al (1 994) that 1 $1_0$ = 80 ± 17 km/sec/Mpc. The 95% confidence limits on $H_0$ are the interval (50, 100) km/s/Mpc.

The key project aims to secure the distances of two more Virgo galaxies, which will markedly reduce the uncertainty as to the mean cluster distance. A total of 20 galaxy distances is being sought in the key project to secure the calibration]] of secondary distance indicators in general, and thus to reduce the uncertainty in the Hubble Constant to 10510.

*Acknowledgements.* The key observations disc ussed herein were made with the Hubble Space Telescope, which is managed for NASA by the Spat<! Telescope Science Institute. We thank STScI director, Bob Williams, for encouraging us to observe N4100 early in the life of the Key Project to determine the extragalactic distance scale. We thank the WFPC2 team for furnishing an instrument which is up to the job. We acknowledge NASA grant 2227 from STScI.

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'J,'able 1: Calibration of the IR TF Relation

| Galaxy | $\Delta V_{20}(0)$ | $H^{abs}_{-0.5}$ |
|---|---|---|
| N4178 | 298 | -20.8s |
| N4192 | 476 | -23.25 |
| N4206 | 318 | -20.68 |
| N4294 | 252 | -20.'25 |
| N4380 | 329 | -21.25 |
| I3322A | 296 | -20.2s |
| N4450 | 3s9 | -22.97 |
| N4498 | 226 | -20.'26 |
| N4501 | 597 | -23.88 |
| N4519 | 304 | -20.28 |
| N4532 | '271 | -20.58 |
| N4535 | 423 | -'22.57 |
| N4651 | 461 | -22.37 |
| N4654 | 3s? | -22.23 |
| N4698 | 460 | -22.63 |
| N4758 | 21 I | -19.80 |
| M33 | 205 | -20.12 |
| M31 | 540 | -23.49 |
| N300 | 235 | -19.50 |
| N2403 | 265 | -21.05 |
| M81 | 450 | -23.42 |
| N5204 | 155 | - 19.:?3 |
| N5585 | 211 | -19.3s |
| Hol V | 106 | -1'/.04 |

*Sources* : Aaronson et d 1982, Aaronson, Mould, & Huchra 19S0, Freedman 1990.

# Appendix

Evidence for substructure in the Virgo cluster is discussed by Bingelli et al (19s7), Huchra (1988), Pierce and Tully (1988 - PT) and Tonry et al (1990). To quantify our discussion]) of the uncertainties arising from this substructure we have generated a number of idealized models of the Virgo cluster with the following genera] properties.

(1) The cluster is located at a mean distance d from the observer.

(2) Galaxy distances are normally distributed from the cluster center with variance $r^2$.

(3) Errors in distance modulus of 0.3 mag arise from use of the Tully-Fisher (TF) relation.

With this prescription it is possible to explore the parameter space of models which fit the distribution of Virgo galaxy distances inferred by PT. Inspection of Figure "[ shows that within the small number statistics of the PT data Model 1 with a large value of r (3.5 Mpc) is a satisfactory fit. Smaller and larger values of r are not good fits.

Two component models are motivated both by the appearance of the distribution of the P'J' data in Figure 7 and by examination of the much larger TF database of Fouque et al (1 992). in Fouque's data the mean TF distance of spirals within 2° of M49 is 0.67 ± 0.20 mag larger than that of spirals within 2° of M87. M87 and M49 are the two brightest ellipticals in Virgo. The simplest two component model to provide a satisfactory fit to the data in Figure 7 is Model 4.

We now experiment by increasing d and calculating the probability that, of two galaxies drawn from the distribution, one will be closer than 14.9 ± 1 .2 M pc and the other closer than 17.1 ± 1.8 Mpc. In Model 5 (a one component model) we see that, if d is increased to 19 Mpc, the probability that these constraints will be satisfied is approximately 14%. We can confidently rule out Model 6 with d = 22 Mpc.

Models 7 and 8 quantify the upper limits on two component models. We can confidently rule out Model 8 with its mean distance d = 20.5 Mpc.

Table 2: Virgo Cluster Models

| Model # | d Mpc | r Mpc | Comment |
|---|---|---|---|
| 1 | 17 | 3.5 | Fits PT data |
| 2 | A: 16<br>B: 22 | 2<br>2 | A is 2/3 total cluster<br>B is 1/3 |
| 3 | 16 | 1 | |
| 4 | A: 16<br>B: 22 | 1<br>1 | Fits PT data<br>A B (2:1 as above) |
| 5 | 19 | 3.5 | Fits constraints 14% of time |
| 6 | 22 | 3.5 | Fits constraints 5% of time |
| 7 | A: 16.5<br>B: 22.5 | 1<br>1 | Fits constraints 16% of time |
| 8 | A: 18.5<br>B: 24.5 | 1<br>1 | Fits constraints 4% of time |

# Figure Captions

Figure 1. The location of Ml 00 in a cone diagram of the Virgo cluster. Galaxies from cz = O to 3000 km/see are shown.

Figure '2. The position of M 100 in the x-ray Virgo cluster. The ROSAT map is from Bohringer et al (1 994)

Figure 3. Galaxies in ZCAT (Huchra 1994) in the indicated interval of Right Ascension, Declination with redshift in the interval (- 1000, 2500) km/sec.

Figure 4. The three calibration checks ou the Expanding Photospheres Method from Cepheid distances. The datapoints are the LMC (SN1987A) MIO1 (SN1970G) and M100 (SN1979c). The clashed lines enclose 90% confidence limits on the ratio of EPM to Cepheid distances.

Figure 5. Calibrators of the Infrared Tully Fisher Relation. Solid symbols: Freedman (1 990), open symbols: Virgo galaxies from Aaronson et al 1982, crosses: members of the M1 01 group. The dashed line is the calibration of Freedman (I 990).

Figure G. Deviations from a uniform Hubble flow. Solid circles: clusters of galaxies with Tully-Fisher distances. Solid triangles: EPM data of Schmidt et al (1994). Open symbols: brightest cluster members from Lauer & Postman (1 994). There is no evidence that a different value of the Hubble Constant pertains inside and outside the distance of the Coma duster at $v_{CMB}$ = 7200 km/sec.

Figure 7. (for Appendix) Monte carlo realizations of Model 1 (solid) compared with the scaled distribution] of distances tabulated by Pierce & Tully (1988) (dot-dashed curve). Lower graph: model 4.

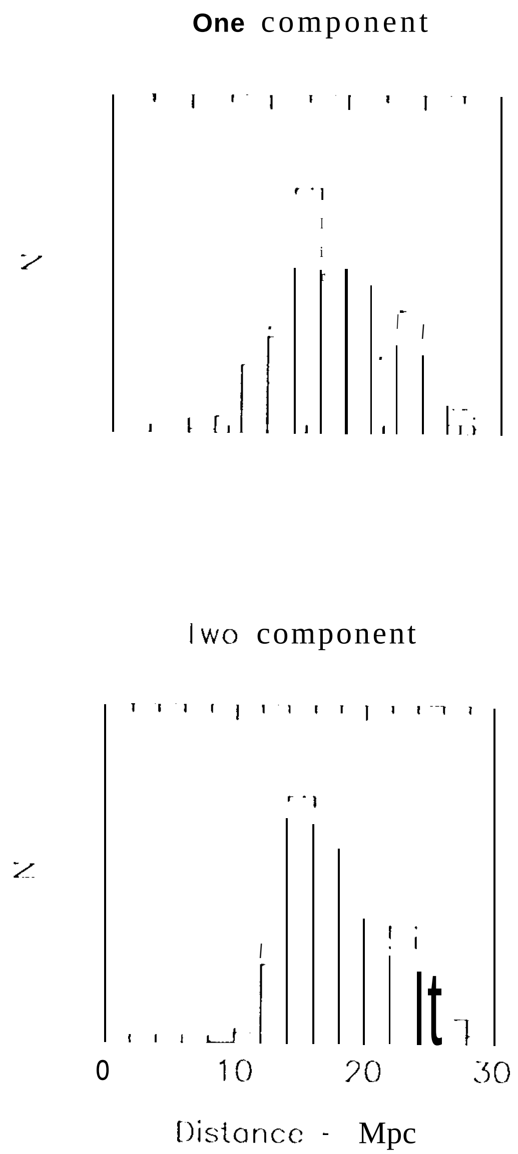


Figure 7: *Monte carlo realizations of Model 1 (solid) compared with the scaled distribution of distances tabulated by Pierce & Tully (1988) (dot-dashed curve). Lower graph: model 4.*

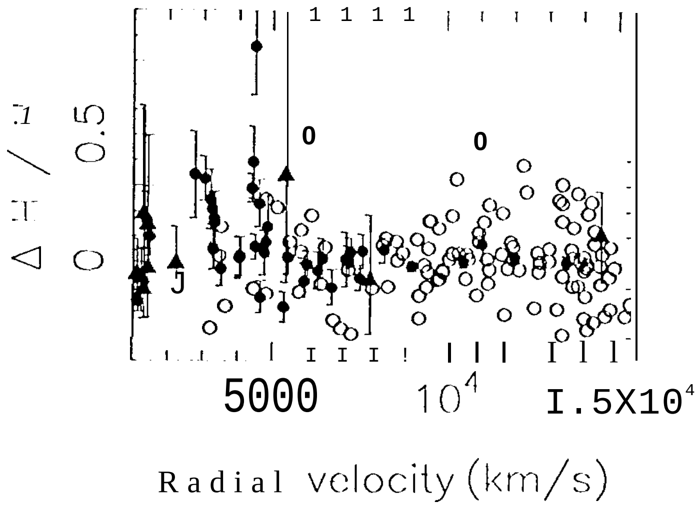


Figure 6: *Deviations from a uniform Hubble flow. Solid circles: clusters of galaxies with Tully-Fisher distances. Solid triangles: EPM data of Schmidt et al (1994). Open symbols: brightest cluster members from Lauer & Postman (1994). There is no evidence that a different value of the Hubble Constant pertains inside and outside the distance of the Coma cluster at $v_{CMB}$ = 7200 km/sec.*

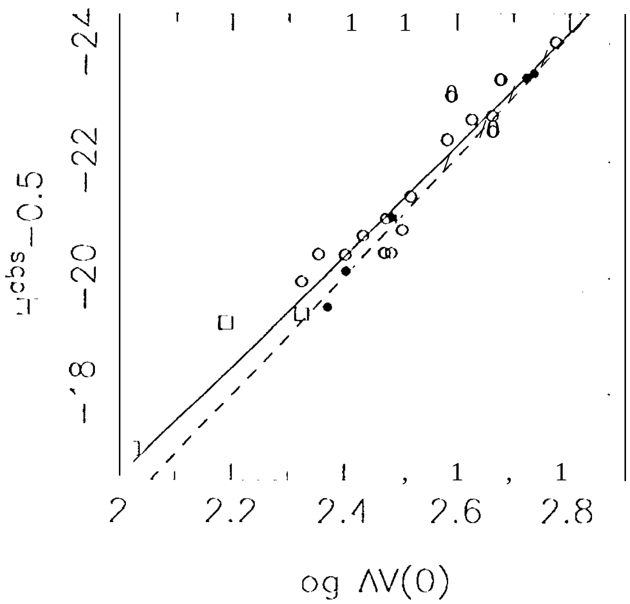


Figure 5: Calibrators *of the Infrared Tully Fisher Relation.* Solid symbols: *Freedman (1990),* open *symbols: Virgo galaxies from Aaronson et al 1982,* crosses: *members* of *the M101 group.*

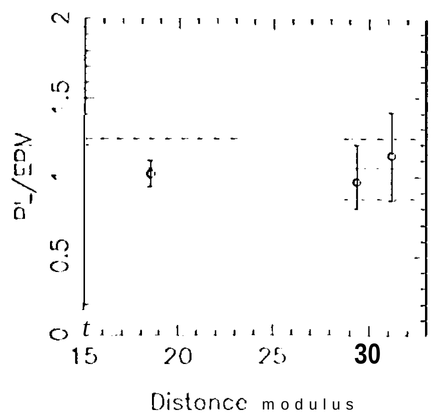


Figure 4: *The three calibration checks on the Expanding Photospheres Method from Cepheid distances. The datapoints are the LMC (SN1987A) M101 (SN1970G) and M100 (SN1979c).*

[redacted]

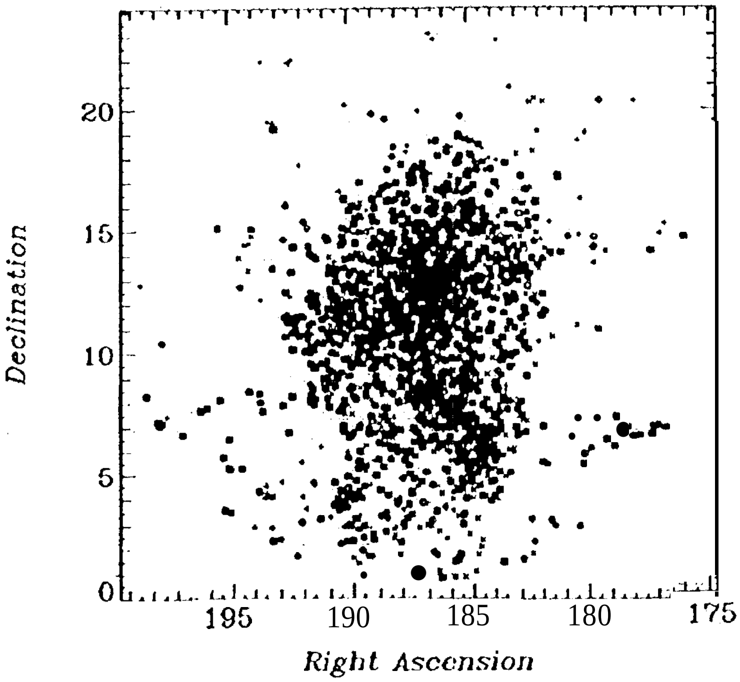


Figure 3: *Galaxies in ZCAT (Huchra 1994) in the indicated interval of Right Ascension, Declination with redshift in the interval (-1000, 2500) km/sec.*